THE DIURNAL VARIATION IN CEILING HEIGHT BENEATH STRATUS CLOUDS

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The diurnal changes in various meteorological elements have been the subject of careful investigation for many years. The diurnal tendencies of pressure, temperature, and wind have received more attention than those of the other elements, and are generally recognized and understood. The increasing demand for accurate forecasts of ceiling and visibility placed upon forecasters by commercial aviation interests has directed attention to the desirability of considering the diurnal tendency in the elevation of stratus cloud and fog when formulating airway forecasts.

During a study which was begun in an attempt to arrive at a reliable method for forecasting the diurnal changes in ceiling height beneath stratus cloud and fog in the San Francisco Bay region, some interesting observations were made which have resulted not only in a better knowledge of the ceiling height changes, but also in a clearer conception of the processes involved and in increased ability accurately to forecast the time of formation and dissipation of the cloud in the region in question.

The results of the study are here presented, in the hope that some of the precepts derived for forecasting the behavior of stratus cloud and fog might be applicable in some degree to other regions and therefore helpful to forecasters.

The stratus cloud of the San Francisco Bay region is the inland extension of the "high fog" common to the entire coastal area of California. In the bay region the cloud forms during the evening or night, and dissipates during the morning, usually clearing away by noon or soon thereafter, but occasionally persisting all day. Before proceeding with the diurnal changes which the cloud undergoes it is desirable to touch briefly upon the air mass structure and the processes involved in its formation.

During the summer, when the cloud is most common, a remarkably homogeneous stratum of cool, moist air overlies the bay region as well as the other coastal areas of California. This air, obviously of maritime origin, is fed into the coastal regions from the semipermanent Pacific HIGH which reaches its maximum strength during the summer. Overlying the moist stratum, at an altitude ranging from less than 1,000 to more than 2,500 feet, is found comparatively warm and very dry air. The surface of discontinuity between the two air strata is manifested as a very sharp temperature inversion. While the temperature increases sharply with increase of height at the inversion level, the relative humidity decreases. The strength of the inversion is so great as to prevent an appreciable amount of mixing of the two strata.

The stratus cloud forms entirely in the moist stratum, usually just below the inversion level. Although referred to as stratus, the cloud actually begins as many incipient cumuli. As they increase in extent, the cumulus masses merge to form the cloud sheet which, for observational purposes, is usually classed as stratus. According to Bowie[1] the predominating factor in the formation of the cloud is the radiational cooling which occurs near the upper surface of the moist stratum. He explains that air rich in water vapor is selectively highly absorptive and likewise selectively highly radiative of terrestrial radiation; and that, conversely, dry air is diathermanous to such radiation. This leads to pronounced cooling near the upper surface of the moist stratum, causing instability and finally cloud formation. If this theory be correct we should expect to find the lapse rate in the moist stratum to be equal to or in excess of the dry adiabatic. That the cloud begins to form as a cumulus tends to indicate such a lapse rate, and, as we shall see later, the relation between the cloud height and the surface relative humidity tends also to bear out the theory.

Some authorities prefer to place mechanical turbulence ahead of radiation as the predominant factor in producing the cloud. That turbulence does not control the diurnal changes which the cloud undergoes is brought out effectively by a comparison of figures 4 and 5, showing a minimum of cloudiness occurring simultaneously with a maximum of wind movement, and vice versa. Perhaps each of the two factors plays its part.

Figures 4 and 5 also tend to discredit the idea that the cloud simply drifts in from over the ocean.

Furthermore, an examination of the specific humidities in the bay region during almost any period in which stratus cloud forms at night and dissipates during the day will reveal the fact that the air-mass types prevailing at night and during the day do not differ from one another except in respect to thermal differences and the presence of cloud, thus definitely eliminating air-mass change as a possible cause of the diurnal variation in the cloud occurrence.

If the cloud is of convective origin, forming in the upper portion of a layer of unstable air which is limited above by an inversion through which convection cannot penetrate, it should be expected that a very definite relation would exist between the altitude of the base of the cloud, i. e., the ceiling height, and the depression of the dew point of the surface air. More specifically, there should be about 225 feet of ceiling for each degree of depression of the dew point. In order to test for this condition, the average amount of ceiling height for each degree of depression of the dew point was computed for each hour of the day. Records for a period extending over 5 summer seasons were used for this purpose. The averages are shown in figure 2. It is significant that at 5 a. m., about the hour of sunrise, there are on the average 227 feet of ceiling for each degree of depression of the dew point. This remarkable agreement between theory and the observed ceiling heights strongly indicates a lapse rate at least equal to the dry adiabatic, with complete interchange of air between the ground and cloud levels.

An increase in the surface temperature causes an increase in the depression of the dew point and therefore an increase in the amount of vertical displacement necessary to cause saturation; in other words, an increase in surface temperature raises the saturation level. With a convective condition prevailing, such an increase in saturation level must be followed by a rising ceiling. That the temperature rises during the morning hours, even though the sky is overcast, is shown in figure 3, which gives the average hourly temperature. These averages are based only on temperatures observed beneath a sky from six- to ten-tenths overcast with stratus cloud. It appears that no influence other than the in-

[1] Bowie, E. H. The Summer Nighttime Clouds of the Santa Clara Valley, California. MONTHLY WEATHER REVIEW, February 1933, pp. 40-41.

coming solar radiation can be responsible for the rise in temperature. The inflow of warm air from regions not covered by the cloud does not seem possible and is not observed. In connection with the effect of the sun upon clouds, Sir Napier Shaw [2] states that clouds in general have very little to fear from the sun because so large a part of the solar energy which strikes them is reflected, while the small portion of it which is absorbed is in part radiated back to the sky and thereby lost. The logic of his statement is supported by the fact that observations of the upper surface of the bay-region stratus cloud have revealed that the altitude of its upper surface changes but little, although exposed to the direct sunlight.

About 78 percent of the solar radiation incident at the upper surface of the cloud is said to be reflected and thereby lost. A part of the remaining 22 percent penetrates the cloud, and probably goes largely to increasing the air temperature near the ground. Such an increase in temperature causes an increase in the saturation level and, therefore, in the ceiling; it often leads to complete dissolution of the cloud when the saturation level is so increased as to become higher than the inversion. This leads to the somewhat paradoxical statement that the sun, while beating down upon the upper surface of the cloud, evaporates it progressively from the base upward and not from the top downward.

Summarizing: thus far it has been found that the cloud may be considered to form in an unstable air mass limited above by an inversion through which convection cannot penetrate, and that it is dissolved by a similar process during the period of the day when the saturation level is increasing. This knowledge has resulted in improved ability to forecast accurately the time of formation and dissolution of the stratus cloud in the bay region. It is readily apparent that the cloud cannot form until the temperature has decreased enough to lower the saturation level to or below the inversion level. Again, during the daytime, complete dissolution can occur only when the increase in surface temperature has raised the saturation level to or above the inversion level.

This principle forms the fundamental basis for forecasts of the diurnal behavior of the cloud. However, full advantage of its value has probably not been obtained, due to lack of precise information on the height of the inversion at various periods of the day. In the absence of such information, the pressure difference between Oakland and Eureka has been used, for correlation purposes, as a substitute for the height of the inversion, because the pressure difference is roughly proportional to the height of the inversion. This fortunate relation is due to the fact that during the summer season the pressure over Oakland and Eureka is about the same at the same altitude in the warm air above the inversion level; therefore, differences in the sea-level pressure at the two stations are caused by differences in the density and depth of the layer of maritime air overlying the respective stations. With Eureka on the immediate coast and the depth of the overlying maritime air subject to only small changes there, the larger changes in the pressure difference between the two stations are closely related to the changing depth of maritime air over Oakland.[3] Correlation of these three elements, i. e., pressure difference between Oakland and Eureka, saturation level at Oakland based on surface temperature and humidity data, and the time of formation (or clearing) of the cloud, has given very good results. It must be expected, however, that when exact information on the height of the inversion becomes available, better results will ensue.

Returning to the analysis of the diurnal march of the ceiling height, it should be pointed out that the discussion which follows deals with a sky which is from six to ten-tenths overcast with stratus clouds. This is important because of the fact that the upper surface of the cloud is a most effective radiator of long wave-length radiation and an excellent reflector of solar radiation.

The idea that during the morning hours after sunrise the increase in surface temperature occurs first, and in turn gives rise to an increase in the saturation level and the ceiling height, is supported by the observed fact that the number of feet of ceiling for each degree of depression of the dew point decreases during this interval (fig. 2). This means simply that, with wind movement at its usual low value during the morning, the process of convection requires time to adjust the ceiling to the increasing saturation level, and that the rise in ceiling height therefore lags.

It appears that by 3 p. m. there is an excess of outgoing over incoming radiation, for at that hour both the temperature and the ceiling begin to decrease (figs. 1 and 3). By reference to fig. 2 it will be observed that there is still a lack of balance between the ceiling height and the depression of the dew point; i. e., the saturation level is still higher than the ceiling. This would lead us to expect the ceiling to continue to increase; that it does not continue to increase appears to be contradictory, but may be explained in the following manner:

After rising from the ground and reaching the upper surface of the cloud, the air begins to cool by radiation. Because of this cooling its saturation level becomes lower than before, with the result that when it sinks it brings the cloud level down below the saturation level indicated by the surface temperature and dew point. The difference between the saturation level of the air near the ground and that at the upper surface of the cloud during the late afternoon results in an irregular and often a broken cloud stratum. As the surplus of heat near the ground is gradually disposed of, the ceiling lowers and becomes increasingly uniform, with the result that by morning there is created a cloud sheet with a quite uniform ceiling at almost exactly the height which the depression of the dew point would lead us to expect.

The lowest ceiling occurs normally at about 3 a. m., while the average amount of change from midnight until sunrise is quite small (fig. 1). From the foregoing explanation of the diurnal behavior of the ceiling it would at first appear that the lowering tendency should always continue until sunrise. That it does not do so can be explained by the well-known insulating effect of a thick cloud layer. This effect is so well demonstrated by the nocturnal behavior of the stratus cloud that it seems worthy of brief discussion here:

So long as the cloud stratum is broken, and even while quite thin although solidly overcast, a considerable amount of terrestrial radiation passes directly outward to the sky without being absorbed by the cloud. As the ceiling continues to decrease, the cloud undergoes a proportionate increase in thickness because the upper surface does not decrease in altitude. Eventually the cloud becomes thick enough to be practically opaque to terrestrial radiation, restricting the outward flux of radiant energy to the amount radiated from its upper surface. When this occurs, a balance may soon be reached between

[2] Shaw, N. Manual of Meteorology, vol. III, pp. 181-182.
[3] For a thorough explanation of the method for computing the depth of a sea breeze refer to Humphreys, W. J., Physics of the air, pp. 108-110.

the amount of radiant energy supplied by the ground or undersurface and that disposed of by the upper surface of the cloud; this of course results in an unchanging ceiling.

Occasionally the sharp inversion characteristic of the bay region stratus cloud is replaced by a transitional layer between the two air strata; in such cases the cloud thickens both at the upper and lower surfaces. When the

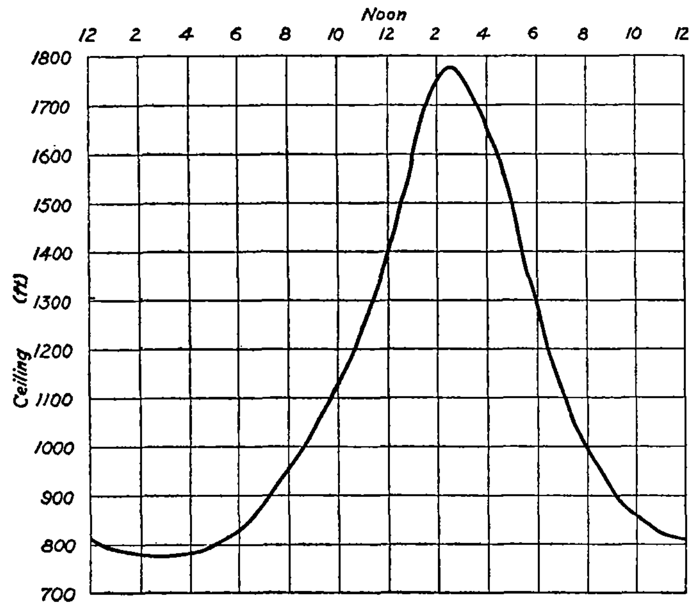

FIGURE 1.—Average hourly ceiling height at Oakland, Calif., during prevalence of stratus cloudiness.

upper surface of the cloud continues to build up after a balance between the radiation supplied by the ground and that disposed of by the cloud has been reached, the ceiling will also rise. This occurs even at night. The influx of a deeper layer of maritime air which permits the top of the cloud to build up to a greater height causes a similar increase in the ceiling height, provided the insulating

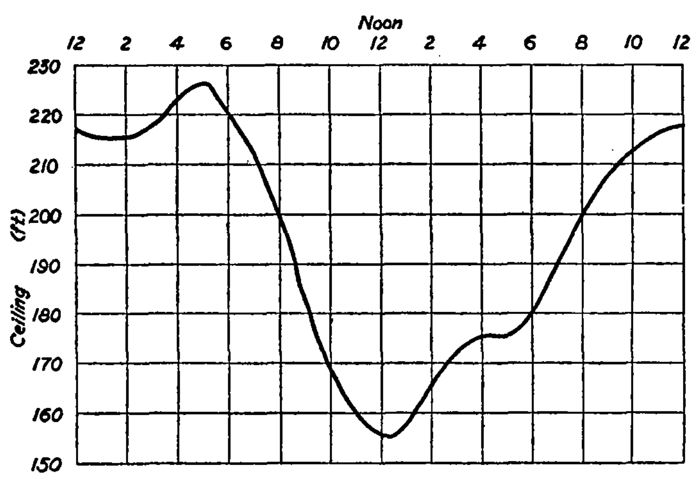

FIGURE 2.—Amount of ceiling for each degree of depression of the dew point.

thickness and radiational balance have already been reached.

In conclusion, it is believed that the principle brought out in the preceding paragraph should find a wide application in the forecasting of the elevation of stratus cloud and fog in various regions, regardless of whether the cloud or fog be associated with a stable or an unstable lapse rate. It may be summarized as follows:

1. If a stratus cloud or a fog of sufficient thickness to be practically opaque to terrestrial radiation overlies ground or any other undersurface the temperature of which is high as compared to the radiating surface of

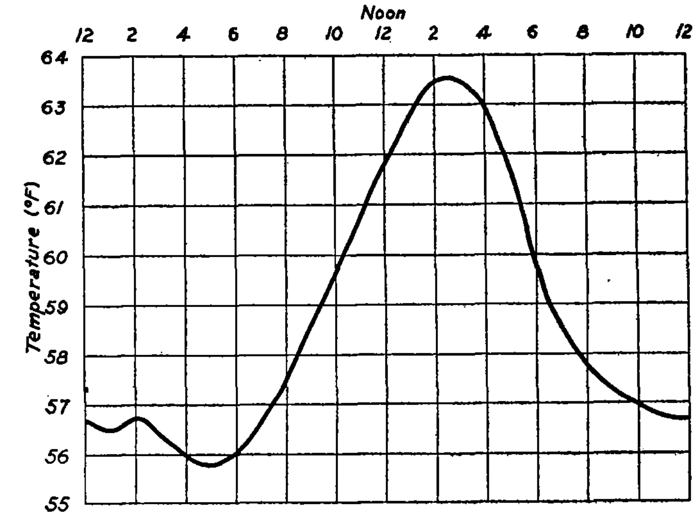

FIGURE 3.—Hourly temperature averages based on temperatures observed beneath broken-to-overcast stratus clouds at Oakland, Calif.

the cloud or fog, there will be a tendency toward rising ceiling; this tendency will continue so long as the supply of heat in the undersurface is maintained or, at night,

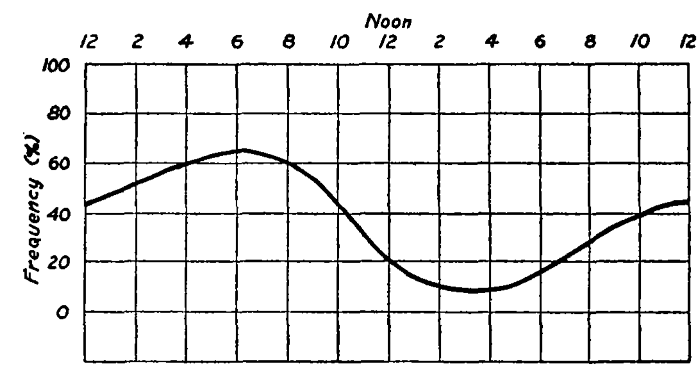

FIGURE 4.—Average hourly frequency of broken-to-overcast stratus cloudiness at Oakland, Calif., expressed in percentage of possible number of times observed.

until the cloud or fog becomes too thin to insulate against direct loss of terrestrial radiation.

2. If a stratus cloud or a fog of any thickness overlies an undersurface the temperature of which is low as com-

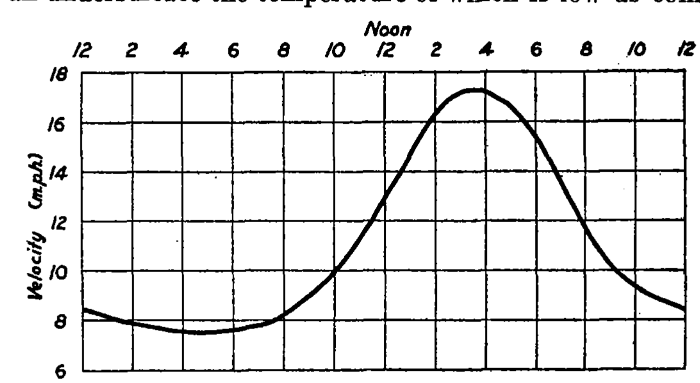

FIGURE 5.—Average hourly wind velocity (nearly all winds having a westerly component) showing a maximum wind velocity at time of minimum cloudiness.

pared to the radiating surface of the cloud or fog, the latter will dispose of radiant energy more rapidly than it is supplied by the undersurface and there will result a tendency toward decreasing ceiling.